World Conference on Timber Engineering
Oslo 2023

THE INFLUENCE OF WOOD COATINGS ON THE MOISTURE BUFFERING CAPACITY OF CLT AND THE INDOOR ENVIRONMENT

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ABSTRACT: The objective of the study was to determine the influence of wood coatings for CLT on the moisture buffering capacity and the indoor environment regarding relative humidity and heating demand. Based on the results of a previous screening of a wide range of coatings, three commercial products were chosen: a flooring oil, an alkyd-based interior wall stain and a fire-retardant stain that were considered to provide both, i) high water vapor permeability to maintain wood's hygroscopicity, and ii) adequate protection of CLT under storage, transport, installation and service. A climate chamber test revealed a good moisture buffer capacity of untreated CLT and a limited one of CLT cladded with gypsum. CLT's glue lines in the frontal plane were not found to affect moisture dynamics. The flooring oil and the wall stain reduced the practical moisture buffer value by 39% and 10%, respectively, as compared to the uncoated CLT. CLT coated with the fire-retardant stain had an even higher practical moisture buffer value than uncoated wood, which is explained by the stain's pronounced hygroscopicity. In all elements tested in a heat flux experiment, the theoretical U-values were higher than the experimentally obtained and simulated values. Hygrothermal energy simulations using a room of 50 m^2 as 'reference model' showed that wood's moisture buffer capacity is beneficial for the indoor environment, by means of passive regulation of RH and lower energy demand for humidification and dehumidification.

KEYWORDS: fire retardant, heating demand, indoor environment, moisture buffering, U-value, wood coating

1 INTRODUCTION

Hygroscopic materials change their moisture content (MC) dependent on the ambient climate. As climate conditions permanently vary in real-use conditions and the inertia of sorption, a hygrothermal equilibrium with its surrounding environment is hardly attained [1]. This material property to absorb and desorb moisture and thereby to moderate the indoor variations in relative humidity, RH, is referred to as moisture buffer capacity, MBC [2,3]. The MBC may be utilized to improve indoor climate [e.g. 4] and save energy [e.g. 5,6,7]. Regarding wood, the MBC has been determined in many studies on a wide range of products including solid wood [e.g. 8], plywood [e.g. 9], paneling [e.g. 10], wood-based insulated panels [e.g. 11] and furniture [e.g. 12]. The challenge of fully utilizing wood's MBC is that wood products are usually coated for improving their aesthetics and technical properties; these coatings may significantly reduce the MBC [13,14,15].

The objective of the present study was to determine the influence of coatings for cross laminated timber (CLT) made of Norway spruce (*Picea abies*) on the MBC and the indoor environment regarding RH and the building's energy demand. As producers of CLT claim a need for surface treatments that are industrially applicable, the premise was to find mechanically resistant coatings that protect CLT under storage, transport, installation and service but at the same time maintain wood's hygroscopicity.

2 MATERIALS AND METHODS

The methodological apporach of the study is shown is shown in Figure 1.

In an initial screening, a literature and market study as well as pre-tests on the water vapor permeability, moisture buffer capacity, scratch resistance and blocking were carried out on clearwood specimens to identify potentially suitable coatings for industrial CLT production. Based on those results (not shown in this paper), three commercial coatings were chosen for further

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https://doi.org/10.52202/069179-0056

investigations on CLT: a flooring and furniture hardwax oil (RMC Oil Plus C, Rubio Monocoat, Dal, Norway), a waterborne alkyd interior wall stain (Lady Pure Nature, Jotun, Sandefjord, Norway) and a fire-retardant (FR) stain (NT Deco, Nordtreat, Vantaa, Finland). The latter is a certified Euroclass B-s1, d0 treatment for CLT. The coatings were applied according to the producers' specifications on five CLT-elements and one solid wood element with a dimension of 100 x 100 x 60 cm^3 (width x height x thickness). The commercial CLT-elements (KLH Massivholz GmbH, Teufenbach-Katsch, Austria) were composed of five-layers made of Norway spruce (*Picea abies*) glued with an polyurethane adhesive. Uncoated CLT and CLT cladded with gypsum of 12.5 mm thickness served as references. In addition, an uncoated solid wood element was included to study a possible influence of the glue lines in the frontal plane of CLT (Table 1).

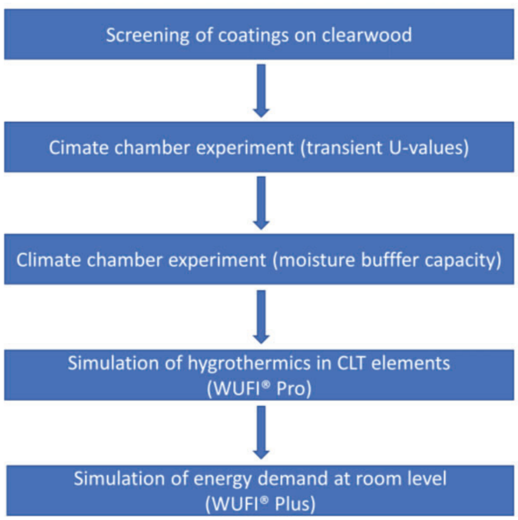

Figure 1. *Methodology of the study*

Table 1. *CLT-elements used in the climate chamber experiment and hygrothermal model. FR = fire retardant*

Element	Coating	Application rate, wet [g/m^2]
1. CLT	/	
2. CLT+gypsum	/	
3. CLT	Hardwax oil	23
4. CLT	Alkyd stain	79
5. CLT	FR-stain	350
6. Solid wood	/	

The elements were installed in a two-room climate chamber that simulated a steady outdoor climate of -2°C/50% and a fluctuating room climate of 23°C/75% and 23°C/33% for 8 h and 16 h, respectively (Figure 2). The interior conditions followed the climate regime described in the NORDTEST protocol to determine the practical moisture buffer value, $MBV_{practical}$ [2]. Before testing, five of the six faces of each element were sealed with vapor barrier tape (FLEX Tape Dampsperre, Isola AS, Porsgrunn, Norway). The unsealed face was exposed to the interior climate. Both air temperature and RH were logged (TH501, Celsicom AB, Varberg, Sweden) in each zone. In addition, the MC in the CLT-elements was logged with electrical resistance moisture meters (MC501, Celsicom AB). In total, five sensors were used, one in each lamella of the elements. The climate chamber experiment provided measurements of the heat flux using plate sensors (TRSYS 02, Hukseflux Thermal Sensors, Delft, The Netherlands), as shown in Figure 3.

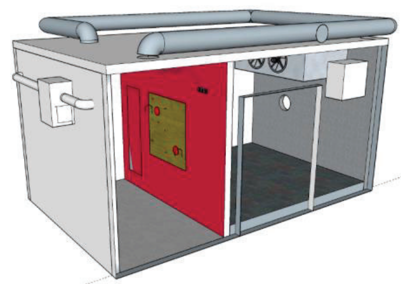

Figure 2*. The two-rooms climate chamber used for measuring the heat flux through the 1 m2 large elements.*

(a)

(b)

Figure 3*. The face of the uncoated CLT-element. The red and blue plates are the heat flux sensors, on the interior (a) and exterior (b) surface of the wall.*

https://doi.org/10.52202/069179-0056

The measurements were then used to calculate the thermal trasmittance, i.e. U-values, during the experiments. After the heat flux experiment, specimens were cut from each CLT-element for measuring the wood density and the MC according to the oven-dry method (Figure 4). In addition to the specimens used for density and MC measurements, five specimens were cut from each CLT-element, which were used for determining gravimetrically the $MBV_{practical}$ according to the NORDTEST protocol [2].

The experimental results from the climate chamber test were compared with modelled sorption dynamics and simulated transient U-values in each of the CLT-elements, employing the HAM (heat, air and moisture transport) software WUFI® Pro [16]. The values of T, RH, density and MC measured during the experiment were used as input data. In addition, the S_d-values of the coatings were used for modelling that had been determined in a dry-cup test according to EN ISO 12572:2016 during the screening phase of the study. Eventually, the experimentally obtained U-values (U_{exp}-values) as well as the simulated U-values (U_{sim}-values) in WUFI® Pro were compared with the theoretical (steady state) U-values calculated according to ISO 6946:2017 (U_{th}-values).

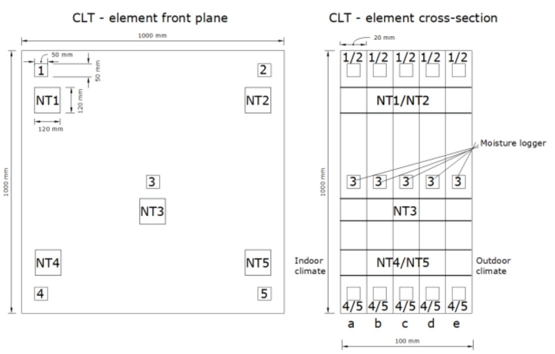

Figure 4. After the end of the climate chamber test, 25 specimens (five per CLT-lamella) were cut from each CLT-element to measure the density and MC (1 to 5). In addition, five specimens were extracted for determining the $MBV_{practical}$ according to the NORDTEST method (NT1 to NT5).

To model the moisture dynamics at room level, the hygrothermal energy simulation tool WUFI® Plus [17] was employed. A reference, a room with an area of 5 m x 10 m was used (Figure 5), which is part of a residential building; therefore, the relevant specifications regarding the indoor environment and HVAC systems were followed as described in SN-NSPEK 3031:2020 [18]. The following scenarios were considered:

Two building systems: i) with CLT/solid timber wall systems both as exterior (Figure 6) and interior walls (Figure 7) and ii) a conventional stud wall system as exterior wall (Figure 8 A) and concrete as internal wall (Figure 8 B). All external walls are insulated and the U-value is 0.18 W/m^{2}K. An overview of the scenarios is shown in Table 2.

For the cases with CLT/solid timber wall systems as external and internal walls, the six different cases that had been tested in the climate chamber and validated using the WUFI® Pro 1D were used.

The sixth case consists of a conventional insulated stud wall, with exterior wooden cladding and interior cladding in gypsum board, and a concrete internal wall with only plaster as finishing in both surfaces.

Two different functions in the HVAC system were considered: i) with humidification and dehumidification and ii) without humidification and dehumidification.

Two different functions in the HVAC system were considered: i) with moisture recovery and ii) without moisture recovery. Today, the vast majority of the HVAC systems include only heat recovery but not moisture recovery, which might be important when combined with hygroscopic materials.

Two different levels of mechanical ventilation rate were considered: i) a rate according to the Norwegian Standard SN-NSPEK 3031:2020 for the apartments and ii) a rate reduced by 50% compared to (i).

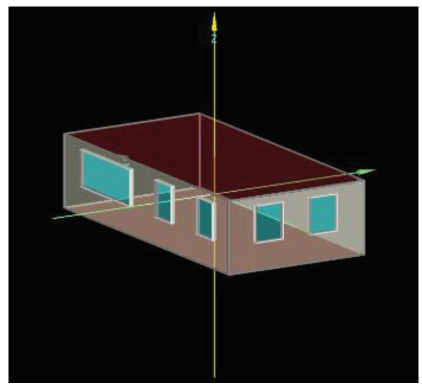

Figure 5. 3D view of the room model used in the hygrothermal energy simulations in WUFI® Plus. The two facades with windows are external walls while the other two are internal walls. The long façade (10 m) and the short façade (5 m) are oriented towards the south and east, respectively.

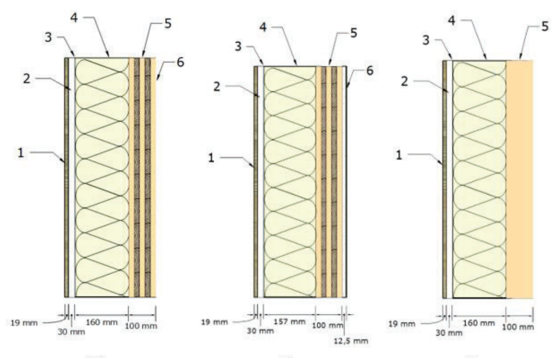

Figure 6. The three different designs of the external walls in CLT/solid timber: (A) with exposed and uncoated CLT-element, which represents the insulated versions of the elements 1, 3, 4 and 5 in Table 1. (B) CLT-element cladded with gypsum, which represents the insulated version of the element 2 in Table 1. (C) exposed and uncoated solid timber, which represents the insulated version of the element 6 in Table 2.

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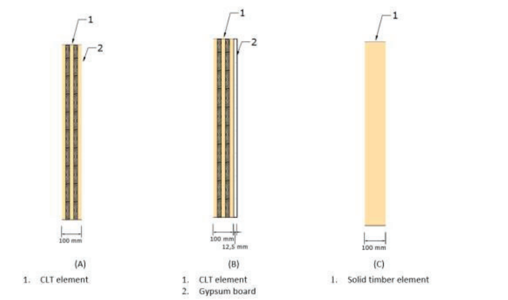


Figure 7. *The three designs of the internal walls in CLT/solid timber: (A) uncoated CLT element,representing the elements 1, 3, 4 and 5 in Table 1. (B) CLT-element cladded with gypsum, representing element 2 in Table 1. (C) exposed and uncoated solid timber, representing element 6 in Table 1.*

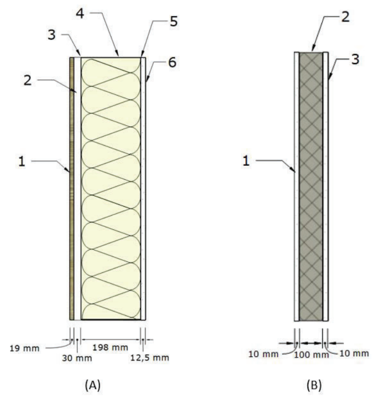


Figure 8*. The exterior (A) and the interior wall (B) for the case #6 in* ***Table 2****, i.e. the case without CLT/solid timber.*

Table 2. *Overview of the wall designs simulated in WUFI® Pro*

Cases	External house wall	Internal house wall
#1	Insulated CLT	Non-insulated CLT, untreated on both surfaces
#2	Insulated CLT with gypsum as interior finishing	Non-insulated CLT wall with gypsum board as interior finishing on both surfaces
#3	Insulated CLT coated with hardwax oil or alkyd stain (S_d = 0.01)	Non-insulated CLT wall coated with hardwax oil or alkyd stain on both surfaces
#4	Insulated CLT coated with FR-stain (S_d = 0.59)	Non-insulated CLT wall coated with FR-stain on both surfaces
#5	Insulated wall in solid timber without glue line in the frontal plane	Non-insulated wall in solid timber without glue line in the frontal plane on both surfaces
#6	Insulated stud wall, with wood panel as exterior cladding and gypsum board as interior cladding	Non-insulated concrete wall, with mortar on both surfaces

3 RESULTS AND DISCUSSION

3.1 MOISTURE BUFFER CAPACITY AND TRANSIENT U-VALUES

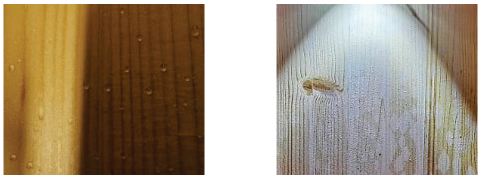
Table 3 shows the $MBV_{practical}$, the S_d-values of the three coatings as well as the U_{th}-values, U_{sim}-values and U_{exp}-values. The $MBV_{practical}$ of 1.06 classifies the MBC of uncoated CLT as "good" and of CLT cladded with gypsum as "limited" [2]. $MBV_{practical}$ of untreated Norway spruce found in the literature range from 0.91 [13] to 1.36 [2,8]. The hardwax flooring oil and the alkyd-based interior wall stain decreased the $MBV_{practical}$ by 39% and 10%, respectively, as compared to the uncoated CLT. A reduction by 10% is rather low compared to those reported in other studies on wood coatings [14,15]. Lozhechnikova et al. [13] found for example that a two-layer coating of linseed oil and a spray laquer reduced the $MBV_{practical}$ by approximately 20% and 70%, respectively. CLT coated with the FR-stain had an even higher $MBV_{practical}$ than uncoated wood, which is explained by the stain's pronounced hygroscopicity due to the FR-actives in the formulation. This hypothesis is supported by the observation of small water droplets on the specimen surface (Figure 9 A) and discoloration most likely due to salt crystalization (Figure 9 B), which occured during the moist RH step in both climate chamber tests (Figure 1).

Overall, the $MBV_{practical}$ of the three coated CLT differ more than the SD-values of the coatings suggest (Table 2). A relationship between the MBV and the S_d-values is not found.

Table 3. *The$MBV_{practical}$, the S_d-value of the coatings as well as the theoretical (U_{th}), simulated (U_{sim}) and experimental (U_{exp}) U-values of the six wall elements tested in the climate chamber.*

Element	MBV [g/m² %RH]	S_d [m]	U-value [w/(m²K)]		
			U_{th}	U_{sim}	U_{exp}
1. CLT	1.06		0.93	0.87	0.79
2. CLT+gypsum	0.28		0.89	0.84	0.78
3. CLT+HW linseed oil	0.65	0.01	0.93	0.88	0.80
4. CLT+alkyd-stain	0.95	0.01	0.92	0.87	0.76
5. CLT+FR-stain	1.61	0.59	0.93	0.88	0.75
6. Solid wood	0.98		1.00	0.91	0.92

For all six elements, the U_{th}-values, calculated according to ISO 6946:2017, are higher than the U_{sim}-values and U_{exp}-values (Table 3). Our results confirm the hypothesis that the moisture adsorption and absorption in wood increases the thermal resistance of the element due to the latent heat of sorption, i.e. the heat released due to phase change of water vapor to bounded water in wood. The findings are in agreement with previous studies that have shown the temperature in wood increased with moisture uptake, increasing in this way the thermal resistance of the element [6,7,19].



(A) (B)

Figure 9. *Water droplets occurred on the CLT-element treated with the FR-stain during the absorption step (A). The discoloration of the surface (B) appeared in the beginning of the absorption step but quickly disappeared again.*

An influence of the three coatings on the U-values does not become apparent (Table 3). This is expected for the U_{th}-values because the thermal resistance of thin materials, with primarily moisture resistive function, like coatings is considered as neglectible and the calculation method does not account for sorption effects. However, we neither observe a significant influence of the coatings on the U_{sim}-values nor the U_{exp}-values although the $MBV_{practical}$ show that the coatings do influence the sorption properties of wood. This suggests that there is no practical difference by means of thermal performance of wood due to moisture uptake between the untreated and treated wood if the latter is coated with highly water vapor permeable coatings.

3.2 MOISTURE DYNAMICS AT ROOM LEVEL

3.2.1 Buffering of RH indoors

Figures 10, 11 and 11 show the minimum and maximum RH indoors in the simulated room when the HVAC system does not include humidification/dehumidification. In Figure 10, the mechanical ventilation is set according to SN-NSPEK 3031:2020, i.e. it is constant at 90 m3/h. In this case, the maximum RH indoors is lowest in case #1 (59.4%) and #5 (59.1%), which is the uncoated CLT-element and the uncoated solid timber element, respectively (Table 2). In comparison, the maximum RH is highest in case #2 (63.2%) and #6 (63.6%), which is the CLT-element cladded with a gypsum board and the stud wall with the gypsum board as interior cladding. The picture is contrary for the minimum RH: the highest values show case #1 (4.9) and #5 (5.0) whereas the lowest values were found for case #2 (3.8%) and #6 (3.4%). The maximum RH is by 4.5% lower and the minimum RH by 1.5% higher in case #5 (most beneficial) than in case #6 (least beneficial). In other words, the wall design with uncoated wood and without gypsum revealed the lowest difference between maximum and minum RH. This behavior is beneficial in terms of passive control of the indoor environment.

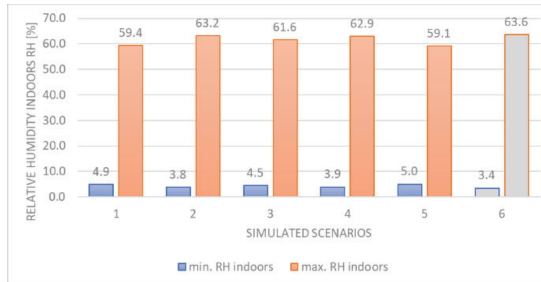


Figure 10. *Simulated minimum and maximum RH indoors in the simulated room without humidification/dehumidification. The mechanical ventilation is set according to SN-NSPEK 3031:2020 and there is no moisture recovery in the HVAC system.*

The moisture buffering effect becomes clearer when moisture recovery is included in the HVAC system (Figure 11). The maximum RH is by 9.4% lower and the minimum RH by 4.6% higher in case #5 (most beneficial) than in case #6 (least beneficial).

A general observation about this set of simulations, i.e. with moisture recovery in the HVAC system (Figure 11), is that the minimum RH is significantly higher than that of the previous set of simulations where moisture recovery was not included in the HVAC system (Figure 10). This means that regardless the type of interior surface, it will be beneficial for the indoor environment if moisture is also recovered, along with heat, in the mechanical ventilation. This seems to be of particular need in spaces/rooms with relatively limited moisture production.

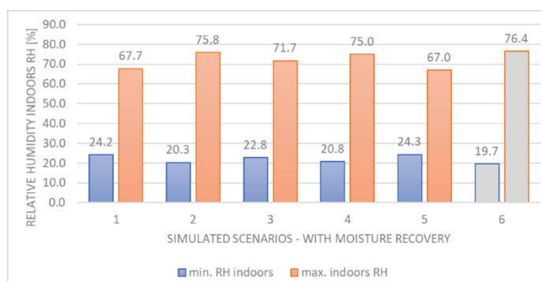


Figure 11. *Simulated minimum and maximum RH_i in the model room without humification/dehumification when moisture recovery is included in the HVAC system.*

Finally, Figure 12 shows the results from the last set of simulations, where the flow rate in the mechanical ventilation was reduced by 50% compared to standard requirements (Figure 10). The reduction resulted in an elevation of both, the maximum and the minimum RH. However, the relationship between the six cases regarding the RH maxima and minima is the same as for the HVAC-systems shown in Figure 10 and Figure 11.

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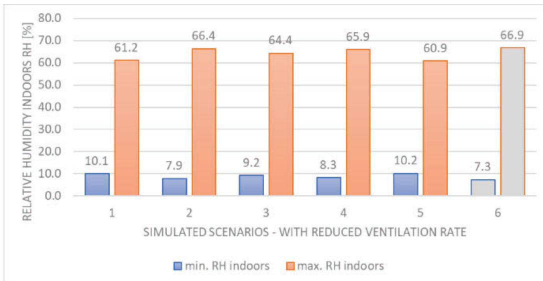

Figure 12. *Simulated minimum and maximum RH indoors in the simulated room without humidification/dehumidification when the mechanical ventilation is reduced by 50% compared to the requirements specified in SN-NSPEK 3031:2020.*

Independent from the type of HVAC-system, the coatings reduce the moisture buffering effect of wood (case #3 and #4, Figure 10, 11 and 12). This applies especially to the FR-stain. Considering the MBV-values (Table 3), the CLT-element coated with the FR-stain (case # 4) should have buffered the RH in the model room best. However, the WUFI® Plus simulations take into account the S_d-values and not the MBV. Against this background, the comparitively high S_d-value of the FR-stain (0.59 m) has a negative impact in the simulations although the MBV of 1.61 W/(m^{2}K) suggests the opposite.

3.2.2 Required energy for humidification and dehumidification

Figure 13, 14 and 15 show the energy used for humidification and dehumidification to maintain the RH indoors within 25% and 60%. Overall, the required energy decreases the better the MBC of the wall system is. However, the impact of the MBC strongly depends on the type of HVAC system.

Figure 13 shows the results of the set of simulations where the mechanical ventilation was set according to SN-NSPEK 3031:2020, i.e. constant to 90 m^3/h without moisture recovery in the HVAC system. Case #5 (uncoated solid timber) requires 477.3 kWh for humidification while case #6 (stud wall with gypsum board as interior cladding) requires 502.2 kWh for humidification and 0.3 kWh for dehumidification. Case #1 (uncoated CLT) shows a similar performance like case #5 and case #2 (CLT cladded with gypsum) shows a similar performance like case #6.

The range of 25 to 60% for indoor RH corresponds to the Indoor Environmental Quality class 2, which is the target range for new buildings. Both, Figure 10 and 12 and consequently Figure 13 reveal a large difference between the need for humidification and dehumidification, which shows that the minimum RH is a challenge in modern residential buildings.

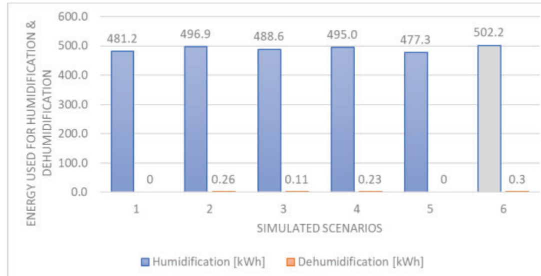

Figure 13. *Energy used for humidification and dehumidification to maintain the RH indoors within 25% and 60% when mechanical ventilation is set according to SN-NSPEK 3031:2020 and there is no moisture recovery in the HVAC system.*

The inclusion of moisture recovery in the HVAC system reduces significantly the need for humidification (Figure 14). In particular, for case #5 (exposed and uncoated solid timber) there is negligible humidification need (0.1 kWh) while for case #6 (stud wall with gypsum board as interior cladding) the humidification need is 4.6 kWh. Case #5 shows also the lowest need for dehumidification (8.2 kWh), which reflects the contribution of this building component to the passive regulation of the RH indoors. In contrast, case #6 shows the highest need for dehumidification (26.9 kWh). As in the other cases, case #1 is similar to case #5, and case #2 is similar to case #6.

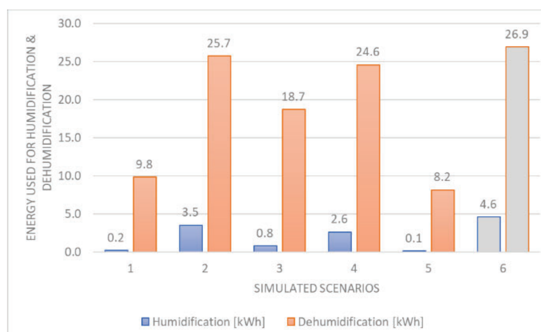

Figure 14. Energy used for humidification and dehumidification when moisture recovery is included in the HVAC system.

Figure 15 shows the results when the flow rate of the mechanical ventilation system is reduced by 50% compared to the standard rate (the indoor air quality (IAQ) was yet exceptional). The results in this set of simulations are similar to the ones of the previous sets.

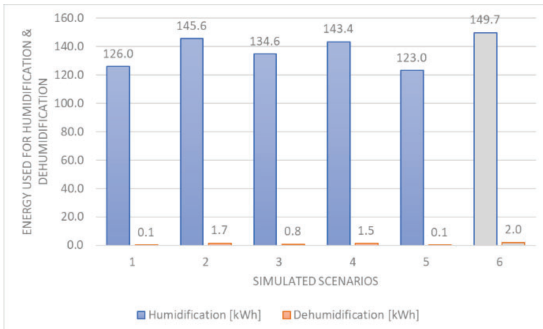

Figure 15. *Energy used for humidification and dehumidification to maintain the RH indoors within 25% and 60% when the mechanical ventilation is reduced by 50% compared to the requirements in SN-NSPEK 3031:2020.*

4 CONCLUSIONS

The study confirms the hypothesis that wood's MBC is beneficial for the indoor environment, by means of RH and energy demand for humidification and dehumidification, as well as for the thermal conductivity of CLT. In other words, there is need to take into consideration the humidity level to calculate a realistic U-value.

Gypsum was found to decrease the MBC of CLT from "good" to "limited" ($MBV_{practical}$ of 0.28). Highly-permeable coatings reduce CLT's $MBV_{practical}$ only slightly. From the practical point of view, a replacement of gypsum is difficult to realize in applications with strict requirements to fire safety. To a certain extent, this might be possible by using an FR-stain, which even increased the $MBV_{practical}$ of untreated CLT from $MBV_{practical}$ 1.06 to 1.61. However, it is to consider that an FR-treatment as its best may improve the reaction-to-fire performance of wood from Euroclass D to B.

Finally, the study on the FR-stain reveals a weakness in the methodology of quantifying the MBC and simulating its impact on the indoor environment and, consequently, on energy requirements related to the HVAC system. The $MBV_{practical}$ of a coating may be high due its hygroscopicity although its water vapor permeability is low.

ACKNOWLEDGEMENT

This study was part of the Build-in-Wood project, funded by the European Union's Horizon 2020 programme under grant agreement No. 862820.

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